Dimensionally Stable Materials for Space Interferometers

B. P. Dolgin
California Institute of Technology
Jet l'repulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

ABSTRACT

Future NASA missions in astrophysics, Earth observation, and solar system exploration that require optical communication, optical and infrared imaging, or high precision astrometric measurements impose very stringent demands for the dimensional stability of precision structures and science instrument components. Examples of near-term missions with critical dimensional stability issues include: the Cassini Imaging Science Subsystem (1SS) and the Space Infrared Telescope (SIRTF). Longer range mission plans call for even more stringent dimensional stability, JPL has identified twenty-six proposed missions with critical dimensional stability requirements.

The objective of this paper is to identify the major mechanisms that influence the dimensional behavior of common optomechanical materials, to identify the mechanisms that arc important for the proposed missions with critical dimensional stability requirements, and to compare the mission requirements with state-of-the-art material and measurement technologies. The dimensional stability of many future space structures is expected to be achieved by a combination of stable materials and active controls, Active controls, however, do not eliminate the need for dimensionally stable materials. Active controls can transfer the dimensional stability requirements from the structures to the mechanical elements of tbc sensors of active controls. Ultrahigh dimensional stability is then required for elements of active systems that arc used to maintain the relative vertex positions of retroreflectors, triangulation bases, Ronchi rulings and sensor mounts, The requirements for the dimensional stability of these elements in some cases can be stricter than 1 Å. "l'his paper discusses the tradeoffs of passive vs. active means of achieving the dimensional stability requirements. The reduction of power consumption and mass, tbc reliability improvements as a function of the dimensional stability of the structural materials for a typical interferometer arc calculated.

Neither the metrology nor the technology of dimensionally stable materials has been developed to tbc level required for some proposed NASA missions. Without the metrological capability, the understanding of materials-related mechanisms for dimensional instability is not possible. Lacking this understanding, the design of stable structures/materials is generally reduced to costly trial and error, A significant effort in the area of dimensionally stable materials is required to make the proposed missions possible.

BACKGROUND

Future NASA missions will require a considerable improvement in the dimensional stability (DS) of materials and structures. Currently, structures can be made passively stable to about onc ppm to tens of ppb levels with reference to a $\Delta T \leq 1K$ or passage of onc month's time at room temperature. In addition, thermal cycling usually creates instability greater than 0.1 to 1 ppm strain levels. Even near-term missions and instruments such as the Cassini Imaging Science Subsystem (1SS) (athermalization metering rods) and the Space Infrared Telescope (SIRTF) (primary, secondary, and tertiary optics) encompass several critical dimensional stability issues, l'eta] strain allowable, pcr year of mission life, is in the range of 0.1 to 2 ppm for some components in these instruments/facilities. Dimensional stability requirements of some missions proposed for the next 10 to 15 years are considerably more stringent than the requirements of ISS or SIRTF, and arc generally beyond available technological capabilities, Table 1 contains a list of proposed missions which will require materials stable on a ppm to ppb level and, even, on a 10^{-12} level. The DS requirements of some missions that define the DS as an enabling technology are listed in Table 2.

Planners t'or the interferometers, telescopes and observatories listed in l'able 2 must assume that nlatcrials/structures state-of-the-art technology will improve as much as one- o-two orders of magnitude by the time of the actual design of the instruments. The cost, life expectancy, and scientific capabilities of these missions will be dramatically affected by breakthroughs in the area of dimensionally stable materials.

TABLE 1 Proposed NASA Missions with Enabling or Enhancing Dimensional Stability Requirements[1,2]

	PROPOSED MISSIONS	Enabling Enhancing	Technology Freeze	Launch Date
Astrophysics				
LAGOS	Laser Gravitational Wave Observatory in Space	E	2009	2015
LDR	Large Deployable Reflector	E	2003	2008
1,01	Lunar Optical Interferometer	E	2006	2010
MIGO	Millin]ctcr-Wave Interferometer Grrivity-Wave Observatory	E		
SALSA	Synthesis Array for Lunar	E	2007	2012
SMILS	SubMillimeter Imaging Line Survey	E	2006?	2012?
SMME	SubMillimeter Explorer	E	1998	2002
SIRTF	Space Infrared Telescope	H	]994	2000
SOFIA	Stratospheric Observatory for Infrared Astronomy	H	1991	1998
VLBI	Very Large Base Interferometer, Advanced	H	2000	2006
Extra-Solar				
AIT	Astrometric Imaging Telescope	E	1998	2003
IBIS	Interferometer Based Imaging System	E	2006	2010
OSI	Orbiting Stellar Interferometer	H	1997	2003
POINTS	Precision Optical Interferometer in Space	H	1999	2004
Solar System Exploration				
	Advanced Imaging Spectrometer	H		
	Mercury Orbiter	11		2002
MSTI	Multi-Spectral Thermal Imager - Advanced	H		
	Optical Communications Reception Network	H	2005?	2010?
STDS	Space Technology Demonstration Sy Jan].....	H		
Earth Observation				
	Advanced Observation Systems	11		
AIRS	Atmospheric Infrared Sounder - Advanced	11		
GMPR	Geostationary Microwave Precipitation Radiometer	E		
	Global Change Technology Initiative	11		
SWIRLS	Stratospheric Wind Infrared Limb Sounder	11		
TES	Tropospheric Emission Spectrometer	H	--	

Many future submicron or sub-ppm dimensional stability requirements exceed the limits of modern technology. The composite struts used in the metering truss of the Hubble Space Telescope (11S'1') is an example of large scale state-of-thc+rrt structure. Table 3 lists some relevant properties of the HST truss. When exposed to the low Earth orbit environment, the HST metering truss is stable at the level of several microns only.

Several nlatcritil-related issues may be significant if the HST metering truss design concept is considered for future missions. This strut is made of a carbon fiber reinforced epoxy matrix composite. l'hc near zero CTE was achieved by the appropriate choice of the fiber volume and layup, and by repetitive thermal cycling of the strut, This cycling caused microcracking of the epoxy matrix and, most likely, some fiber/matrix and interlaminar delamination. One possible result, when heated, might be that the truss would not expand smoothly (at the submicron level). Many proposed missions cannot afford these types of perturbations. Another issue is the strut length contraction on orbit due to moisture desorption[3]

The entire length of the HST metering truss structure contracted about 250 microns witbin the first year in orbit which caused a change of focal distance' over 25 mm, The average rate of this contraction; at the end of 1991, was 0.06 μm/day. While active focus capabilities were successfully usc on HST and other composite benches such as JPL's Wide Field Planetary Camera, these focus mechanisms can be costly and present a risky single point failure. Appropriate hermetic coatings for composites may both reduce and slow down this shrinkage[6,7] However, hermetic coatings do not eliminate intrinsic instability of composites that is discussed later in this paper.

TABLE 2. Proposed NASA instruments and missions for which dimensionally stable materials and structures arc defined as enabling technologies].?

	Aperture meters	Mirror Figure micron	integration Time	Distance Between Mirrors meters	Pointing Accuracy arc sec	Mission Life years	Tempera-ture Range K	Estimated DS Requirements. ppm
Telescopes								
APT	1-3	0.3 rms		meters			<100	0.1 - 1
IBIS	1-4	.05μm/1m	days				70-80	
LDR	10-20	5 rms		meters	0.1	10-15	100-120	1 - 10
SIRTF	0.7-1	0.3 rms			0.25	3-6	<3	1-1o
Interferometers								
LOI	1	0.3 rms		3-4		10	70-80	0.0}-0.1
MIGO	1	1 rms					100-150	1
SMILS	3.6	10 rms	0.5 h	$6\cdot10^7$	2	2-4		0.1 - 10
SMME	2.5	15 rms			1			0.1-10
SALSA	2	0.05 rms		30				0.1 - 10
GMPR	4.5	10 rms				5		

TABLE 3. Dimensional Stability Properties of the Metering Truss of the Hubble Space Telescope[3,4]

Strut Geometry	1.676 m x 58.4 mm ID
Coefficient of Thermal Expansion (CTE)	0.03 to 0.08 ppm/K (Low Earth Orbit Environment)
Water Absorption	0.4 to 0.6 weight %
Elongation after Thermal Cycling	5 microns (3 ppm) over 30 cycles I 3 microns (8 ppm) over 50 cycles
Hysteresis on Thermal Cycle	1 to 2 ppm

DEFINITIONS OF DIMENSIONAL STABILITY

Dimensional stability can be defined as a system's ability to retain geometrical properties related to the system's performance in its operational environment. Dimensional stability is not a single or unique material property but rather a term which describes material properties or responses related to specific mission requirements. As such, dimensional stability encompasses all acceptable spatial changes in any given physical property such as geometrical size, mass distribution, or reflected wave front distortions. These changes can be a function of temperature, time, stress, pressure, material composition and changes in composition including sorption and desorption, material structure and its changes, radiation, electrical and magnetic fields, gravitational and inertial loads. Characteristics of interest include changes in length, width and thickness (volume); changes in shape or form (out of plane deflections such as bend or twist); as well as geometrical optical properties of reflectors, coatings, gratings, and rulings. Dimensional stability can be both a material's and a "system's" ability to retain geometrical properties [elated to the system or the instrument performance. Dimensional stability can depend on both the service environment (temperature, pressure, loads, radiation, etc.) as well as the material's history (c. g., thermal hysteresis, creep, and fatigue).

DS is not a unique material or structural property, For example, a reflector that is very stable mechanically may appear to be very unstable to an incoming beam of light. A very stable reflector may not appear to be stable when the distances between different points of its surface are measured. A perfect part of a gravity wave observatory may be inappropriate as a part of an inter ferometer. "l'his chapter describes the different meanings of 1)S for different applications and different environments.

Geometrical and Topological Aspects of Dimensional Stability

Future NASA missions will utilize dimensionally stable materials for three broad classes of systems: optomechanical structures, optical reflecting and refracting elements, and zero-gravity experiments, Structures such as optical benches and truss systems maintain the relative positions and orientations of critical elements of the instruments. The primary function of optical elements is to focus the radiation of given wavelengths. A stable zero-gravity experiment should not produce a changing gravitational environment around a proof mass. The meaning of dimensional stability is different for each of these three types of systems.

The dimensional stability of mechanical structures is expressed in the distances from one surface to another. For mechanical structures, dimensional changes of the order of a percent can cause warpage and buckling of structures. Changes in dimensions of tens of microns can cause misfits of machined parts and loss of focus in an optical imaging system. Micron level mismatches in the joints and trusses of astronomical instruments can cause severe vibrations and render the instruments uncontrollable. Submicron errors in triangulation bases can invalidate the measurements of laser interferometer-type systems.

The dimensional stability of an optical element is defined in terms of wave front errors produced when light is reflected from or transmitted through the element in question, Because of historical reasons, the reflective properties of an optical element are often described in terms of the properties of an equivalent ideal reflector or an ideal lens. By definition, the equivalent ideal reflector (lens) produces the same wave front as the real optical element that is being characterized. It can be shown that the wave front error description and the surface error of an ideal reflector description are two equivalent descriptions. Dimensional stability requirements of the optical system are often expressed in terms of the dimensional stability of the equivalent ideal reflector.

Real optical elements differ significantly from ideal reflectors and lenses. Unlike the real optical elements, idea] reflectors (lenses) reflect (refract) the light only at the surface, Real reflectors permit light to penetrate deep into the surface layer. Real reflectors can have scratches and irregularities that are that do not obey the normal distribution law: $\exp(-x^2/2\sigma^2)$, where x is the wavelength of the irregularity and the σ is the standard deviation, When the wave front errors are large, the shape of the optical element is nearly identical to the shape of the equivalent ideal reflector (lens). When these errors become small, non-ideal properties of optical reflectors rrnd lenses must he taken into consideration.

The dimensional stability description of reflective optical elements depends on the wavelength of the incident light, Electromagnetic radiation is not reflected from the top surface of a mirror but penetrates into the material. The penetration depth can be as shallow as 500 **A** for visible light and IR, and as deep as several microns for sub-mm radiation. I'bus, wave front errors of the reflected radiation depend on the average material properties through the thickness of the surface layers of a mirror. Materials having a perfect surface, but having defects in the material structure below the surface. will exhibit a degraded optical wave front[8,9] Similarly, materials with au uneven surface but a uniform average makeup within the penetration depth over the mirror surface can appear stable and smooth. '1'bus, dimensional stability of a mirror depends on the wavelength of the tool used to measure it. A similar situation exists in reporting surface roughness, where the STM and interferometer measured surface roughness can be significantly different, especially for diamond turned surfaces,

Dimensional stability of mirrors depends on both structural stability of the bulk of the rnir ror and the optical stability of the near-surface layers (including coatings). Temporal changes as well as environmental factors such as temperature gradients and Fluctuations, radiation and atomic oxygen can change the relevant properties of materials near the mirror surface. If the penetration depth changes, the mirror may behave as if it were deformed. An appropriate design should couple geometrically stable DS substructures with optically stable DS surface layers and coatings.

The dimensional requirements of gravity wave cictcctiot~-type experiments are defined in terms of mass distributions and accelerations. For example, a gravity wave observatory requires submicron control of the centers of gravity f'or all substructures of the observatory. For the most part, gravity wave detection experiments are not concerned with surface locations or surface finishes. The stability of mass distribution functions determines the meaning of DS for this class of systems. Appropriate designs should couple geometrically stable 1)S nuitcrials/structures with gravitationally stable DS structures to produce a system with the integral gravitational stability higher than the DS of its parts

The discussion below deals mostly with mechanical dimensional stability The major variables that determine dimensional stability are: time, temperature, heat fluxes, radiation environment, and material history.

TRADEOFFS: PASSIVE AND ACTIVE MEANS OF ACHIEVING STABILITY

The structural dimensional stability of instruments can be enhanced by means of active controls. One can design a multi-level, multi-feedback-loop active control system that is limited only by the accuracy of its sensors and the resolution of its actuators. The penalties for the introduction of active controls are higher cost, weight, complexity, energy consumption, and heat dissipation, as well as lower reliability. To make the system simpler, the amount of feedback loops and the number of controls are minimized. Intrferometric sensors are replaced by sensors based on Ronchi rulings. Passive triangulation bases take the place of fully optically controlled references, sometimes called "optical trusses". However, active controls do not eliminate the need for dimensionally stable material. Controls merely transfer the dimensional stability requirements from the entire structure to the sensors of active control systems,

An optical interferometer is the distance measurement sensor of choice for large structures. Interferometers can measure submicron displacements of mirrors separated by seemingly arbitrary distances. The light for the interferometer can be provided by either a laser or a bright astronomical object, However, interferometric sensors need triangulation points, reflectors, reflector supports and other elements with very stringent dimensional stability requirements, sometimes reaching the subangstrom levels. Thus, triangulation and optical interferometry system designs transfer dimensional stability requirements from long strut structures of astronomical instruments to the optical reflectors and triangulation bases of the controls' sensors. Examples of these tradeoffs in the dimensional stability requirements for different elements of typical astronomical instruments are presented below.

Mirror Alignment in Stellar Interferometers

An interferometric planet detection mission can use the light of a central star to focus the optical system. The mirror arrangement is such that the signal from the star is cancelled inter ferometrica ally. At the same time, the off-axis signal from the planet is not cancelled. Thus, a faint signal from a planet may be detectable near a bright star, Control systems are designed to minimize the signal from the star. The requirements for mirror alignment in these interferometers are often much more stringent than those of conventional telescopes.

A typical interferometer may require that two I -meter-diameter minors separated by 3 to 4 meters are aligned better than 1 arc second, Usually, this alignment must be maintained by dimensionally stable trusses or an optical bench. The 1:4 ratio of mirror diameter to mirror separation is typical for optical interferometers. Alignment to I arc second (= 5.10"6 rad) means that the relative displacement of the edges of the mirrors is less than 1 m $\cdot 5{\cdot}10^{-6} = 5$ μm. This 5-micron tolerance has to be maintained by the 4-meter structure between the mirrors. Thus, the relative length changes of the support structure must be maintained with the accuracy of 5 micron/4 meters, or about 1 ppm. This alignment must be maintained both in a changing thermal environment and over the mission lifetime.

The long term passive minor alignment of interferometers is very difficult to achieve with existing structural materials. The extent of these difficulties depends on the specifics of the mission, For example, on the Moon (1 .OI mission) the temperature variations can be as high as 200 K. Thus, without thermal control the LOI requires material uniformity of I ppm/200 K = 5 ppb/K. A low Earth orbit environment (S01 and AIT missions) requires only 1 ppm/50 K = 20 ppb/K uniformity given the $\Delta T = 50$K assumption, State-of-the-art materials cannot approach a 5 ppb/K uniformity required of supporting truss structure exposed to a large temperature excursion on the Moon. The achievement of 20-ppb/K uniformity of the struts maintained over a 5-year low Earth orbit mission lifetime can be the subject for a very strenuous R&D effort. Significant control of thermal excursions could be expected to relax the thermal strain allowable by at least one order of magnitude, yet still place considerable challenges on DS materials.

Additional controls, laser interferometers, and triangulation schemes can relax requirements for the passive alignment of the mirrors. However, these elements introduce strict dimensional stability requirements for a different set of elements.

Laser Interferometers and Triangulation Bases

Laser radiation can be used to measure and adjust the precise positions of all reflectors that comprise an astronomical instrument, In some instruments the relative location of two mirrors provides sufficient information for the control system. Control systems for the majority of other astronomical instruments require precise measurements of several intermediate points. These systems use triringulrrtion to determine the positions of reflectors located on or around the mirrors rrnd supporting struts. The triangulation base for these measurements can be maintained either passively or by another interferometer.

The dimensional stability of the triangulation bases of some proposed interferometers (as opposed to telescopes) is beyond state-of-the-art technology. The error budgets generally require that the stability of the triangulation base should be 1 to 2 orders of magnitude better than that of the controlled structure. l'bus, a mechanical triangulation base (e.g., 0S1 Mission) requires a fully exposed materials to be stable at the 0.001 -ppm level over the integration time of several minutes even after several years in space. The optical part of the triangulation base can require reflectors with optical dimensional stability on the level of 1 **A** (0S1 mission) or even 0.02 **A** (POINTS). In addition, in pure optical triangulation, the relative positions of the vertices of the retroreflectors must be maintained with angstrom accuracy (Lunar Interferometer, OSI mission, POINTS). These optical-based requirements cannot be satisfied by present knowledge of material behavior.

Wave Front Corrections

Mirror figure imperfections limit the range of astronomical applications for a telescope or an interferometer. Figure errors can cause aberrations and reduce angular resolution. Controlled segmented and flexible secondary and tertiary optics mrry be introduced to compensate for wave front errors.

Wave front correction may introduce very strict requirements on the uniformity of the thermal DS of the primary mirror. If a nonsegmented telescope mirror expands or contracts uniformly, only the focal length of the mirror changes, As a result, the telescope is easily refocused to compensate for this change. However, if this mirror expands nonuniformly, then the wavefront will be distorted. in this case, changing the shape of a controlled optical clement somewhere further in the optical path may compensate for the major distortions caused by the out-of-shape deformation. If this compensating optical element is segmented, generally only 3 degrees of freedom of these segments have to be controlled, " The major difficulty arises when the primary minor is also segmented.** in addition to the tilt, thermal loads may change the curvature (i.e., focal distance) of the segments of the primary mirror. Focal distance corrections for individual segments may be much more difficult to achieve. Additional actuators on the compensating elements may be required. l'bus, the requirements for the uniformity of the thermal DS may become more stringent.

Weight, reliability, and energy savings due to stable materials

To quantify the weight, energy, and reliability improvements which can be realized by the implementation of materials with better dimensional stability we have chosen the Focused Mission Interferometer[10] (FMI) as a representative instrument. l'here arc three major reasons for this choice: 1) the instrument is sufficiently well defined; 2) the instrument is representative of n larger class of space based interferometers; and 3) an extensive modeling of the instrument has been performed under the Controls/Structure Interaction (CSI) program. This experience with the instrument serves as a guarantee that the model of the structure used in this paper is not oversimplified.

The model described in Fig. 1 is the minimal complexity model that still incorporates optics/structure/control interactions. Light comes in from some distant source. The light is reflected off a mirror on one body (B_2 in Fig. 1) to a detector on another body (B_1 in Fig. 1). Body 1 is assumed to be connected to the "ground". The mirier is capable of translation and rotation. The variables of interest are the lengths of the struts connecting the two bodies. The outputs of interest arc the optical path length

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" The 3 degrees of freedom that are controlled include: motion along the optical axis and two tilt angles with respect 10 the optical axis. l'here are 3 more degrees of freedom related to the segment motion in the plane perpendicular to the optical axis of the system. These in.plane movements do not influence the image quality as strongly as the first 3 degrees of freedom,

** Material for the monolith minor is usually prepared in one batch. Materials for segments are often prepared in different batches. Thin, batch-to-batch variation in material properties is math more important for segmented reflectors.

TABLE 4. The FMI Options

Option	DS of the underlying structure (m)	mass kg	power watt	control loops
I. All passive	10^{-11}	0	0	
II. PZT	10^{-8}	2.5	5	
III. PZT+VC+FSM	10^{-5}	8,8	15	

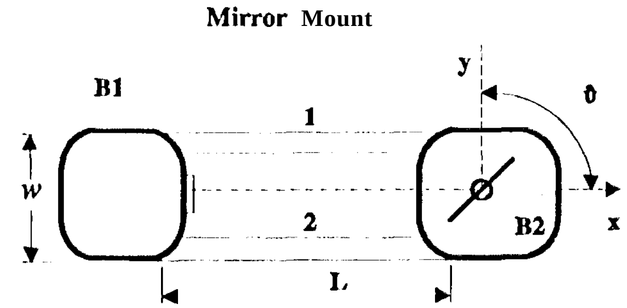


Figure 1. The simplified model of the interferometer.

and the beamwalk on the detector. Simple analysis gives the relationships between the stability of the underlying structure and the requirements of the controls mechanisms. These relations are then used with representative requirements and system parameters to illustrate the possible design options. The details of the calculations are described in Ref 11.

The FMI was designed to have 6 siderostats to collect light in 3 pairs. In the beam train of each pair were a variety of actuators included for two purposes - to adjust the optical path length when the siderostats tilt (as the whole instruments tilts to fill in the aperture); and to compensate for vibration effects on the optical path length and wavefront tilt. The nominal actuators used in Ref. 10 include:

1. 6 siderostats, 2 degrees of freedom.
2. 3 trolleys, each consisting of
   - 1 Timing belt
   - 1 Voice coil transnational actuator
   - 1 PZT transnational actuator
3. 3 FSM's

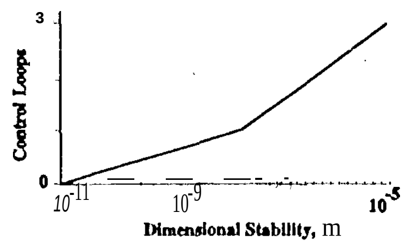


Figure 2. Number of control loops required to achieve the FMI performance goals for a system with a given passive dimensional stability of the structure.

Due to the nature of the design which requires accommodation of siderostat tilt to fill in the aperture, an all passive system does not make sense. If the dimensional stability allows for an Option II in Table 4, it is possible to eliminate the voice coils and

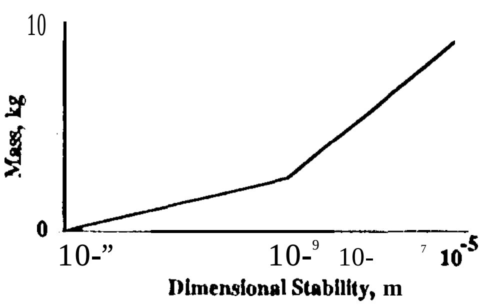


Figure 3. Mass of the required actuators for a system with a given passive dimensional stability of the structure.

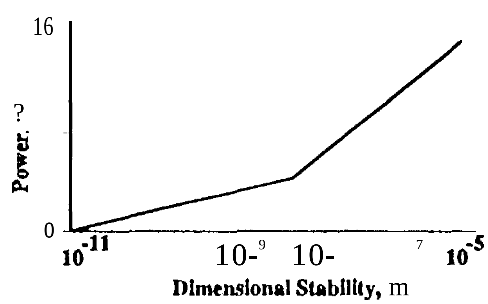


Figure 4. Power consumption of the actuators required for a system with a given dimensional stability of the structure.

FSMs, although this would require PZT's with somewhat more travel. 'l'his option results in mass and power savings of 18.9kg and 30w, respectively. Given a nominal FMI mass of 2277kg, and approximate 600w power consumption, this option represents savings of about 1°/0 and 5°/0, respectively. The savings might double if the required electronics and computer processing equipment arc included. The results of the calculations arc presented in Figures 2.-4.

Improvements in the dimensional stability of materials may lead to a substantial reduction of the weight of the large precision space structures. Given the cost of $100,000 plus pcr pound for the delivery in high orbits, these weight savings may pay for significant portions of R&D costs, An order of magnitude improvement in the state-of-the-art of passive dimensional stability of the building blocks may bring several percent weight savings for structures similar to the proposed Spaceborn Interferometer.

Dimensionally stable underlying structures reduce the complexity, mass, and power consumption of the control system. Low complexity means higher reliability resulting in faster and less expensive development and qualification of the ncw system. Low power dissipation simplifies temperature controls, Also, low power consumption reduces requirements on the power sources rrnd ultimately reduces the weight and the cost of the proposed spacecraft.

PHYSICAL MECHANISMS OF DIMENSIONAL INSTABILITY

Manufacturing and pre/post launch conditions limit the dimensional stability of materials duc to degassing, absorption/desorption (e.g., water desorption), pressure variation, radiation, and other environmental factors. Moving a structure from atmospheric pressure (1 atm) to the vacuum of space increases the dimensions of the part by at least 1 ppm assuming a 100 GPa elastic modulus. Electron, proton rind/or ultra violet radiation exposure can change the chemical and mechanical properties of materials and hence their DS properties Chemical and micro-structural material changes such as phase transitions and grain growth, devitrification and free volume relaxation, molecular cross-linking anti chain breakage can change the dimensions and thermal expansion characteristics of components. In addition, mechanics-related stress relaxation, elastic and plastic deformation, cyclic loads, miclo-yields, creep, and similar phenomena influence dimensions as well. All these processes can degrade dimensional stability. For past and future missions, thermal expansion and contraction have been and will continue to be a major limiting factor in dimensional stability of materials. However, other instability mechanisms will rise in importance as mission science objectives push beyond State-of-the-alt. New instability mechanisms, undoubtedly, will arise as investigations into sub-ppm behavior progress.

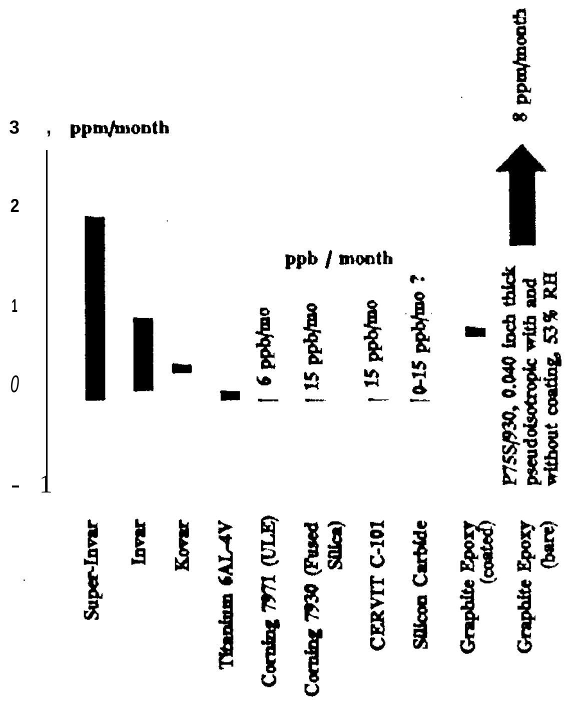
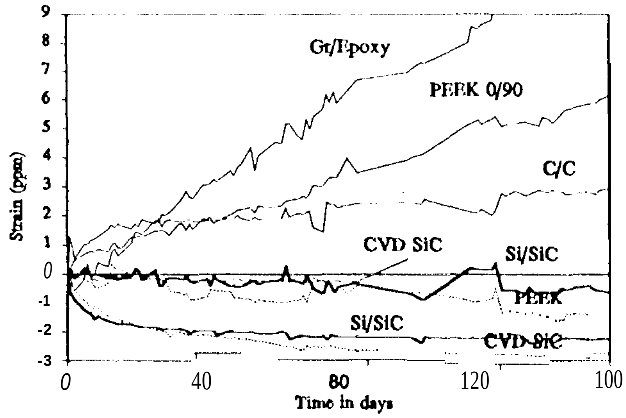


Figure 5. Isothermal (20 - 40 C) Temporal Dimensional Stability of Optomechanical Materials[6,12] (ea. 1989)

Temporal Dimensional Stability

Most materials spontaneously change their dimensions over extended periods of time. Typical long term temporal DS of optical and optomechanical materials[6,7,12-15] ranges from several parts pcr billion per month (ppb/mo) to several ppm/mo (Fig. 5, 6). 'l'bus, during an average five year NASA mission, the size of components can change from several to hundreds of ppm. in contrast to long term temporal DS, thermodynamic volume fluctuations arc examples of processes that limit DS on the millisecond scale[16] Temporal stability is the term that describes all time dependent processes that lead to changes in the dimensions of materials.



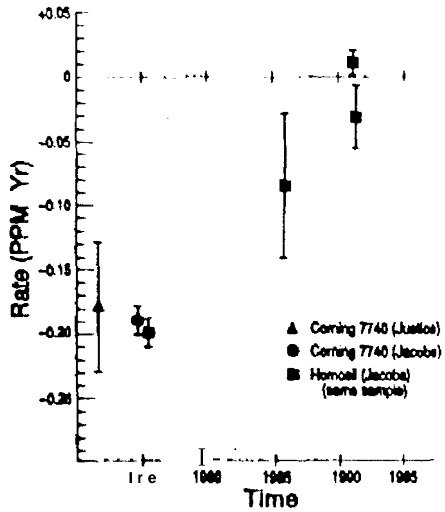


Figure 6. Typical data from an isothermal (30C) temporal dimensional stability experiment. Joint experiment with S. Jacobs, University of Arizona, 1992.

Figure 7. Fused silica. Time dependence of the rate of shrinkage.[14]

The rate of temporal instability is not constant over time. Usually the experimental data shows the rates with near-exponential decay that can be described by at least 2 or 3 time constants. One of these constants is often associated with the metrological set-up (stabilization of the optical contacts, settling of the sample, etc.), There is usually a short and a long term time constant associated with the temporal instability, Figure 7 shows a 2 to 4 year time constant for a fused silica.[14] The behavior of the less stable Silicon Carbide samples in Fig. 6 can be described by a 2-3 month time constant.

Dimensional stability has impacts on optical systems over time scales from a fraction of a second to years. Temporal dimensional stability is especially important in multi-year missions. The overall change in the system's dimensions over its life should be well within the range of built-in compensation such as active focus or passive depth of focus budgets, To qualify a system for a multi-year mission, one should predict both short and long term changes in the dimensions of critical components. For example, feedback loops of triangulation systems for interferometer metrology require that the relative positions of the reference points remain stable over the integration times of several minutes to several hours. Controls for precision structures become very complicated if there is significant instability over time period of milliseconds. Different time scale requirements lead to different design, modeling, and measurement approaches.

Thermal Expansion and Contraction

The thermal environment of a component limits its dimensional stability due to thermal expansion, hysteresis on thermal cycling, and possible acceleration of temporal dimensional changes, A one meter long aluminum alloy part changes its size by nearly 25 microns when its temperature changes by one degree (1 K). In contrast, when a similar size Zerodur glass ceramic material is heated by 1 K around room temperature, it will change its size by less than several nanometers, However, this same Zerodur part exposed to a low Earth orbit thermal cycle can readily change its size by several microns (Fig. 8) after completion of the cycle. On the other hand, the size of the aluminum part may not change significantly after similar thermal cycling. Obviously, neither of these materials satisfies all DS requirements for all systems. Thermal history, temperature uniformity, and the material's response to temperature changes and time are major factors that determine overall dimensional stability.

The description of dimensional stability at the sub-ppm level will require new terminology. For example, Figure 9 compares the behavior of a graphite fiber/aluminum composite with ordinary aluminum. While this composite was not designed for sub-ppm dimensional stability, its behavior and the behavior of the Zerodur sample in Figures 8 illustrate several major peculiarities of ppm and sub-ppm dimensional stability:

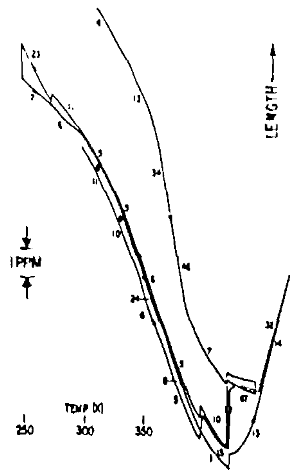


Figure 8. Thermal Cycling of a Zerodur Sample.[10]

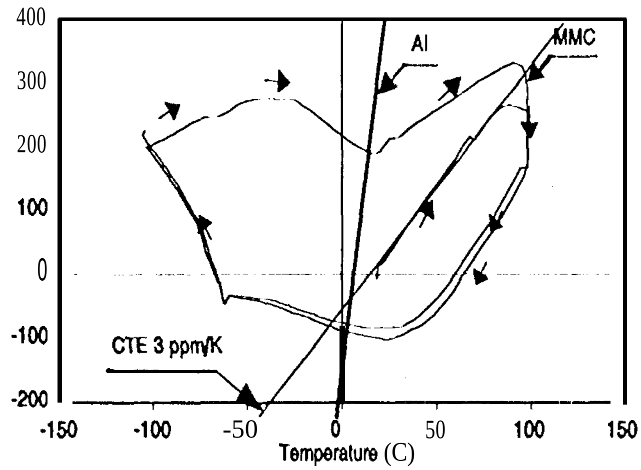


Figure 9. Thermal Cycling of a Graphite Fiber/6061 Aluminum Metal Matrix Composite (MMC) and an Aluminum Alloy.[15]

The extremely nonlinear, nonsymmetric expansion response as a function of temperature makes ascribing a coefficient of thermal expansion (CTE) to this material very difficult. Any CTE would be of questionable value, since obtained values depend on the way they were measured.
Thermal expansion on a ppm level can be highly history dependent. Therefore, the CTE is not strictly a material property but is history dependent.
Hysteresis on thermal cycling can be a major variable in the dimensional stability description of materials at the ppm and sub-ppm level.

For many glass, glass ceramic, ceramic, and metallic materials time dependant phenomena dominate DS properties when the temperature changes are slow. In addition to the classical description of material expansion/contraction behavior via strain-temperature plots, one must consider time-at-temperature effects. Most strain-temperature plots are created by ramping sample temperatures relatively quickly over the range of interest. "Quick" ramping of temperatures is considered to be in the 0.1 to 10 C per minute range. However, when expansion characteristics of the same material are recorded at effective ramping rates much less than 0.1 C per minute, when it takes hours to ramp over the temperature range of interest, a different strain temperature behavior is recorded. One way of generating such data is by changing the sample temperature a set amount, say 10 or 25 C, and then allowing the sample to expand / contract until the rate of change becomes unobservable for a given experimental setup.[16] It can take many hours for a material to stabilize after a set temperature change. All in all, describing material DS behavior by a single CTE number for each temperature is not particularly useful, especially in the sub-ppm strain regime.

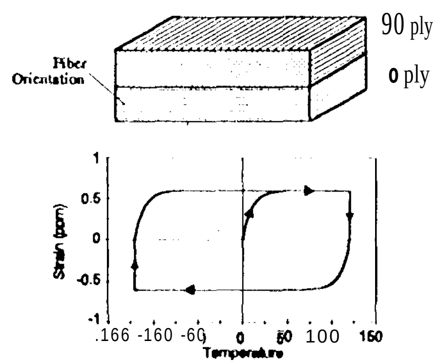


Figure 10. Lay-up of a "zero CTE" composite and its calculated thermal cycle.[17]

Dimensional instability due to thermal gradients and transients in a multi-phase material.

Recently, materials with a nearly zero instantaneous coefficient of thermal expansion over a large temperature range have been developed. These materials are usually at least two phase materials. One of these phases expands when heated, while the other phase contracts. Examples of these materials range from glass/ceramics like Zerodur to "zero CTE" graphite fiber reinforced polymer composites. In the presence of thermal gradients these materials loose their "zero CTE" property. In addition, the dynamics of expansion and contraction cannot be described by coefficients of thermal expansion.

Figure 10 shows how the simplest carbon fiber reinforced material with zero CTE is built. The fiber reinforcement in different layers is oriented in perpendicular direction. The fibers arc much stiffer than the matrix and they shrink on heating. The matrix expands when heated. Thus, when heated, each ply shrinks in the direction of the fibers and expands in the direction perpendicular to the fibers. Given some experience, an engineer can choose the fiber volume fractions which lead to a nearly "zero CTE" sandwich.

Heat flow through a "zero CTE" composite introduces non-zero hysteretic expansion and contraction. When material is heated, the temperature of the outer plies is higher than the temperature of the inner plies. The magnitude of the difference depends on tbc rate of tbc heat flow and the thermal diffusivity of the composite. The calculations for the simplest case is a "zero CTE" composite heated from onc side at a constant rate arc presented in Fig.10. The rate is comparable to the heating rate caused by a sudden exposure of a two layer composite to the Sun radiation in space.

Radiation Induced Instability and Changes in the CTE

All dimensional properties of materials change under exposure to ionizing radiation. Ionizing radiation changes molecular structure and even atomic composition of materials. The mechanisms of dimensional change include defect formation, changes in chemical bond structure, change in free volume of glasses, and nuclear reactions. Organic based materials can change their size by several percent when exposed to radiation levels of 10^7-10^8 rad. Examples of such materials include fiber reinforce composite materials. Inorganic materials, like glasses, change their dimensions by parts per million, Since many mechanisms of dimensional change arc impurity based, the magnitude of change depends on tbc manufacturing process.

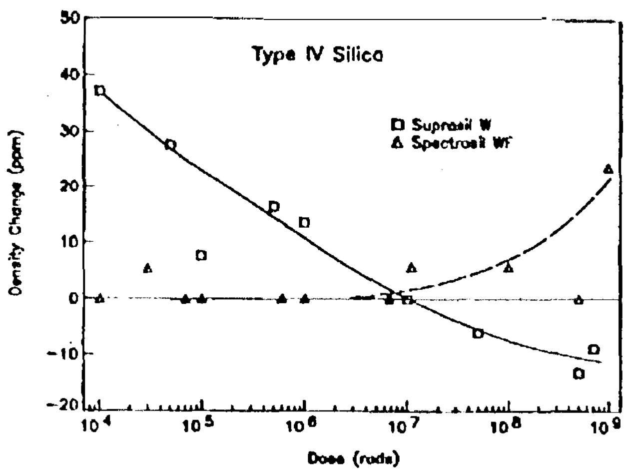


Figure 11. Radiation induced density changes in synthetic silica.[18]

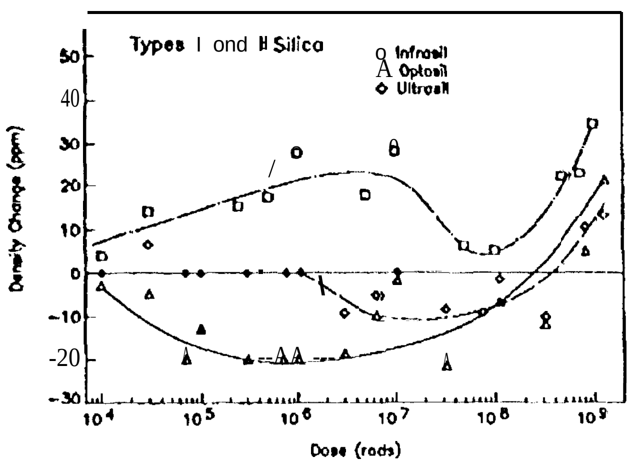


Figure 12. Radiation induced density changes in synthetic silica.[18]

Friebele and co-workers[18,19] have performed a large number of experiments exposing different glasses to a variety of radiation sources. Radiation induced dimensional instability of fused silica is illustrated in Fig. 11 and 12. While general behavior of fused silica is typical for a wide range of glasses, fused silica is relatively stable when exposed to ionizing radiation. Low CTE glasses like Zerodur and ULE arc much less stable. However, even fused silica shows changes in density that can reach 30-40 ppm when exposed to γ radiation as low as 10^4 rad, This density change translates into 10 to 15 ppm of linear dimensional change. Figures 11 and 12 show that to describe the behavior of fused silica varies greatly depending on its manufacturing technology

The performance of the low CTE glasses and ceramics may deteriorate during the life of the mission. For example, ULE glass may satisfy the CTE and the hysteresis requirements in the "as manufactured" state. However, radiation exposure[9] of around the 10^8 to 10^9 rad typical for a long term mission can increase the CTE of the glass to 1 ppm/K. Thus, ULE may become less dimensionally stable than ordinary fused silica.

1)ifferent types of radiation introduce different dimensional instability. "1'here is a significant difference in the mechanisms of interaction and defect distribution for different types of radiation, The dimensional behavior induced by charged particles is complicated by the shallow penetration depth. Unlike y radiation, protons and electrons do not penetrate deeply into materials. Shallow penetration depths lead to sharp variations of exposure (dose) as a function of depth. The dose variation lead to non-uniform damage, internal stresses, and anisotropic behavior of materials. '1'bus, the description of the dimensional stability is complicated by stress relaxation and annealing phenomena.

Changes in phase, composition, and physical/chemical absorption

Chemical and microstructural material changes such as phase transitions and grain growth, devitrification and free volume relaxation, molecular cross-linking and chain breakage can change the dimensions and thermal expansion characteristics of

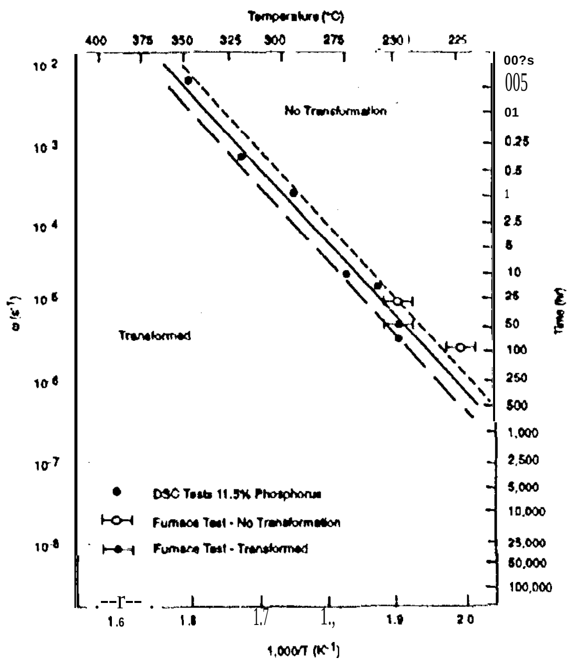


Figure 13. T-T Diagram for electroless nickel. l'hc diagram shows how fast electroless nickel crystallizes at different temperatures (Ref. 20)

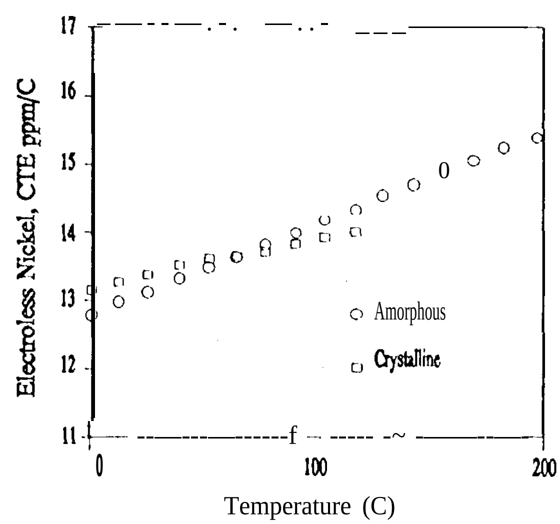


Figure 14, Difference in the CTE of the crystallized rind amorphous electroless nickel.[20]

components. Organic materials and polymer matrix composites exhibit large dimensional instability duc to water sorption and de-sorption.[6] The changes duc to this mechanism can bc as large as several percent. However, dimensional changes due to chemical and physical changes in materials arc not limited to organic and polymeric materials. Electroless nickel, a material widely used in modern optics is a very good illustration of phase transition induced instability.

Dimensional changes in electroless nickel arc caused by a transition from amorphous to crystalline phase. This transition is associated with a volumetric change[36] that can bc as large as 1.3%. The exact value depends on the chemical and structural composition of the starting material. Thus, all environmental conditions being equal, electroless nickel shrinks, The rate of this shrinkage is temperature dependent. Unlike melting or boiling, no matter how low the temperature of the amorphous nickel phosphorous the transformations never stops, Only the rate of transformation changes.

Figure 13 shows the temperature dependence of the rate of transformation as a function of temperature. For example, a sample of electroless nickel left at 225C for a 1000 hours will crystal lize. Thus, its size and its CTE (see Fig. 14) will change by several percent. The transition is gradual. Some of the material will crystallize after 5 minutes at 225C, similar amount of nickel will crystallize after I year at 50C.

Anisotropy and Non-Uniformity of DS Properties

All materials exhibit some non-uniformity of dimensional stability properties. 'l'able 5 describes the inhomogenuity of thermal expansion of common optical materials. Figure 6 of' this paper demonstrates variations in temporal stability of materials. The non-uniformity of the 1)S properties of materials has a profound effect on passive structures that must maintain alignment over a long time or over a wide range of temperature and radiation environments. Materials with inisotropic DS properties make understanding of passive optomecanical systems even more complex.

TABLE 5. Thermal Expansion Inhomogeneity [12]

Material	CTE at 300K ppm/K	Variations of the CTE ppb/K
Aluminum 6061-1'6	23.0	60 (very few data point)
Beryllium VHP I-70A	11.5	130
Borosilicate Glass (Shott)	3.2	30
Borosilicate (Ohara E-6)	3.0	50
P'used Quartz (Amersil)	0.50	5
Fused Silica (Corning 7940)	0..56	2
ULE	0.03	4
Zerodur (Shott)	0.05	40

Isotropic materials that are dimensionally stable on a 10-ppm scale can be anisotropic on the sub-ppm level. The dimensional stability of most metals and metallic mirrors is anisotropic on a 1 ppm scale.[21] Experience with the polishing of large optical mirrors shows a large number of distortions that are explained as "built-in stresses, " " surface irregularities,''ctc, This experience can be the first indication that nearly all materials arc somewhat anisotropic at the sub-ppm level of dimensional stability.

Composite materials are the materials of choice for many future mission application because they provide one of the highest ratios of stiffness-to-weight and strrmg,th-to-weight. In addition, thermal expansion properties of composite materials can be tailored for a particular application, However, composite materials arc highly anisotropic and their dimensional stability properties are poorly understood.

The anisotropy of composite materials limits the application of current dimensional stability theories and measuring techniques. The major differences between the dimensional stability properties of composite materials and isotropic materials are outlined below:
- A composite component that is stable in one direction can be unstable in another direction;
- Well-hchavccl properties of the composite matrix and reinforcement taken individually may not lead to a stable composite because of the presence of interfaces;
- Instability at the matrix/reinforcement interfaces can cause hysteresis on thermal cycling, long term creep, and built-in stresses.

All these mechanisms can cause thermal, temporal, and/or radiation-induced instability

Neither the dimensional stability of isotropic nor anisotropic materials have been studied on tbc sub-ppm level to the degree needed for future NASA missions. The DS mechanisms such as micro-yield, micro-creep, stress relaxation, plasticity, microstructural change (devitrification, phase transformation, and grain growth) may be inadequate to explain sub-ppm dimensional stability, Research in the area of sub-ppm dimensional stability is needed to define mechanisms of instability and to develop materials and material systems that demonstrate DS performance onc to two orders of magnitude superior to the state-of-the-art.

CONCLUSIONS. THE UNIQUENESS OF NASA DIMENSIONAL STABILITY REQUIREMENTS

The dimensional stability of materials and structures is one of the enabling technologies for future NASA missions. However, the technology of dimensionallv stable materials has not been developed to the level required for these missions. The Great Observatories ot'the 21st century introduce stringent requirements that have no analogs in the anticipated industrial projects.

'1'here is a need for NASA to establish pioneering research in the critical technology area of dimensional stability.

Current metrological facilities arc poorly suited for 1)S characterization of composite, precision space structures. Composites arc the materials of choice for many future space structures. However, most modern 1)S facilities have been designed for the characterization of conventional isotropic optical materials rather than nonisotropic composite parts. Multiaxial, noncontact metrology with submicron accuracy appears necessary, Neither the metrology nor the technology of dimensionally stable materials have been developed to the level required for future NASA missions. Without an appropriate measurement capability, the understanding of materials-related mechanisms for dimensional instability is not possible. Subsequently, without this understanding, precision space structure design and verification is reduced to costly trial and error.

A significant dimensional stability research and development program is proposed. The main goals of this program should be: to develop nanometer-level -accurate multiaxial metrology; to understand the physical and chemical mechanisms of material instability on a nanometer level; to characterize the 1)S of selected materials; and to design and demonstrate dimensionally stable materials/components.

Many dimensional stability requirements of the Great Observatories of the early 2 1[st] century cannot be met by 20[th] century technology. To make these missions feasible, NASA must pioneer the research and development of ultrastable materials and structures.

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